

**TRANSPORTABLE SEISMIC DISCRIMINANTS:
THE USE OF CROSS- SPECTRAL MEASUREMENTS TO REDUCE
PARAMETER SCATTER AND IDENTIFICATION ERROR**

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Abstract

Much progress has been made in regional seismic discrimination over the past ten years. Aided by the availability of high-quality waveforms and ground-truth databases, researchers discovered the discrimination capabilities of Lg/P and S/P spectral ratios, especially at high frequencies. However, when spectral ratios or signal parameters which perform well in one geographic area are applied to events in another, the results are typically uncertain or erroneous. This was illustrated during the identification analysis of the Dec. 31, 1992 Novaya Zemlya event: the same data were analyzed by a number of researchers who came to uncertain or conflicting conclusions. For regional discrimination to work in a CTBT context, this problem must be overcome.

The most obvious factors contributing to transportability failure include geographic variability of source and path effects. However, noise and the inherent instability of spectral ratio calculations at low SNR's and restricted bandwidths are also likely factors. Regional seismic spectra rarely follow the model of a flat low-frequency spectrum with smooth high-frequency rolloff. This is especially true for quarry explosions, where long time-delay ripple firing can add harmonic distortion. Good signal processing practice dictates that measurements be made only at frequencies where there is sufficient SNR, which often means the use of cross spectral and system identification methods. This project will extend the discrimination research conducted to date to include these methods. The specific tasks include:

- analysis of existing ground-truth databases using cross-spectral methods,
- a systematic search of cross spectral parameters with discrimination capability,
- discrimination performance comparison of cross-spectral methods with those already made for existing ground-truth databases,
- analysis of new ground truth databases as they are made available by other contractors in this program, and
- statistical assessment of transportability of the cross spectral methods.

Key Words: Discrimination, Spectral Ratios, Cross-Spectra, Ground-Truth Databases

1. OBJECTIVES

The overall objective of this research is to improve regional seismic event discrimination capabilities, reduce identification uncertainty, and search for discriminants which can be transported from one geographic region to another. This is relevant to CTBT verification given the degree of identification uncertainty which has been shown to exist for events in areas with little prior data (Ryall, 1993). Reducing the variability in parameter estimation will be attempted using cross spectral measurements of seismic phases, the motivation for which is described in this paper. The specific tasks are

- to apply cross-spectral measurements to ground truth databases already studied,
- to evaluate the discrimination capability of the extracted cross-spectra,
- to apply and evaluate this discrimination capability for new ground truth databases as they are compiled by other contractors during this program.

2. PRELIMINARY RESEARCH RESULTS

2.1 Overview of the Parameterization Approach

Regional seismic discrimination had been the subject of intense study for the past 15 years. Many approaches have been taken, most notably the parameterization approach, where numerous signal parameters are extracted from waveforms for events with known source type. Other approaches are the machine learning approach (e.g. Dysart and Pulli, 1990; Dowla et al., 1990) and the statistical approach (Shumway, 1995). The parameterization approach receives the most attention because the specific parameters measured are typically chosen on the basis of source physics and seismic understanding (Pulli, 1995).

In the parameterization approach, the ability of a parameter to distinguish between source types is usually expressed in terms of the Mahalanobis Distance for the normal distribution (Duda and Hart, 1973),

$$M_p = \frac{(\mu_{p1} - \mu_{p2})^2}{\sigma_{p1}^2 + \sigma_{p2}^2}$$

where μ and σ are the means and variances, respectively, for parameter p measured for source types 1 and 2. The larger the Mahalanobis Distance, the smaller the overlap in parameter distributions and identification uncertainty (see *Figure 1*).

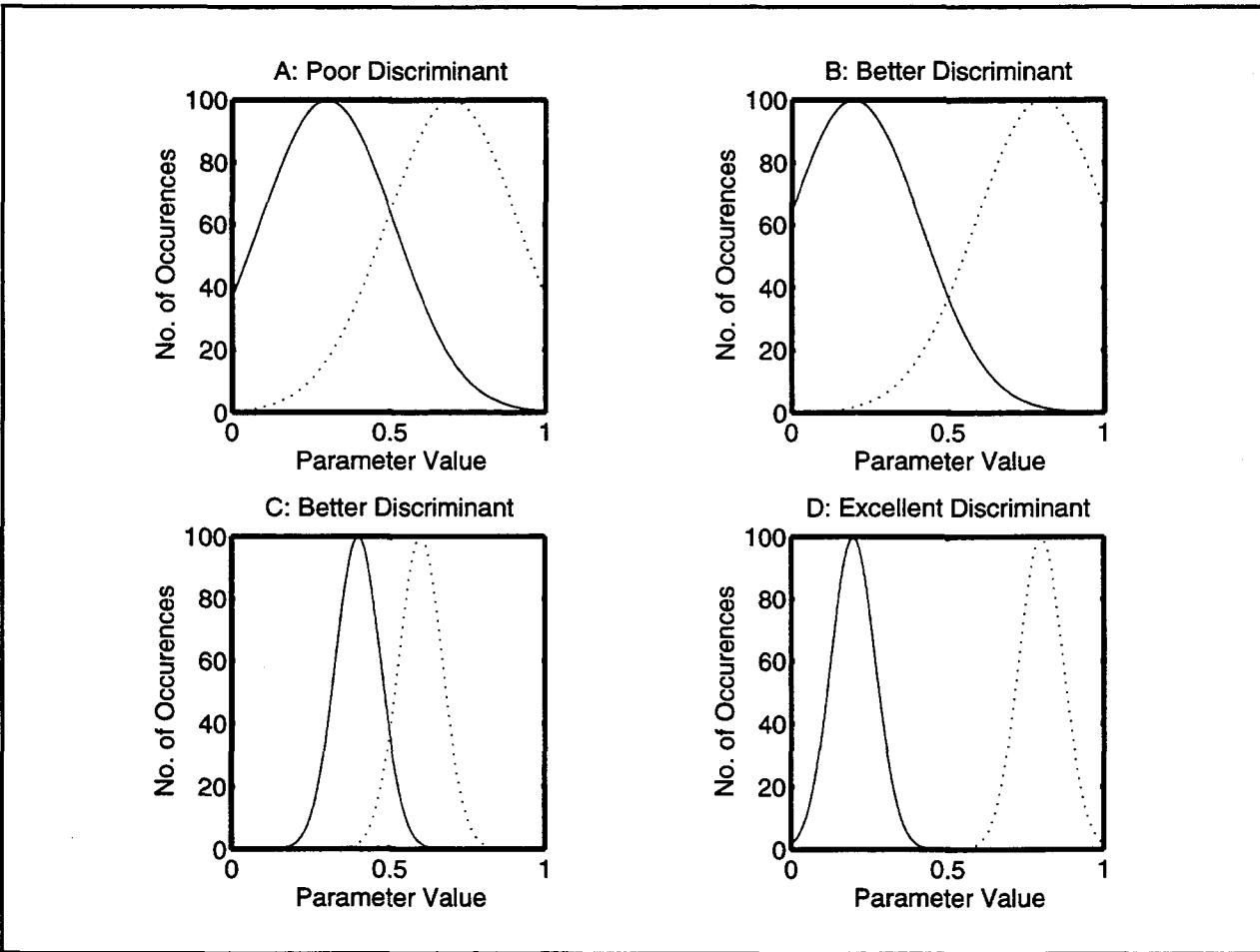


Figure 1. Four hypothetical parameter distributions for two classes of seismic events. In case A, the distributions have similar means and variances, and provide poor discrimination capability. Case B is better, with a larger separation of means but still large variances and overlap. Case C has close means but small variances, with some overlap. Case D is the best, with a large difference in means and small variances.

2.2 Examples of Discriminants at NORESS

To illustrate this concept, consider the 14 discriminant parameter dataset measured at the NORESS array by Pulli and Dysart (1993). Figure 2 shows examples of both good and bad parameters for distinguishing local earthquakes from small quarry explosions. The Pn/Lg spectral ratio measured from 10-20 Hz (Figure 2a) provides good separation of event types, though there is some overlap in the distributions and an earthquake outlier. The Lg cepstral variance (Figure 2b) provides little discriminant capability given the large degree of overlap. Figure 3 shows the Mahalanobis Distances for all 14 parameters. Clearly, parameters 13, 12, and 14 provide no discrimination capability; parameters 2, 11, 9, 6, and 4 provide some discrimination; parameters 1, 3, 10, 5, and 8 provide the best capability.

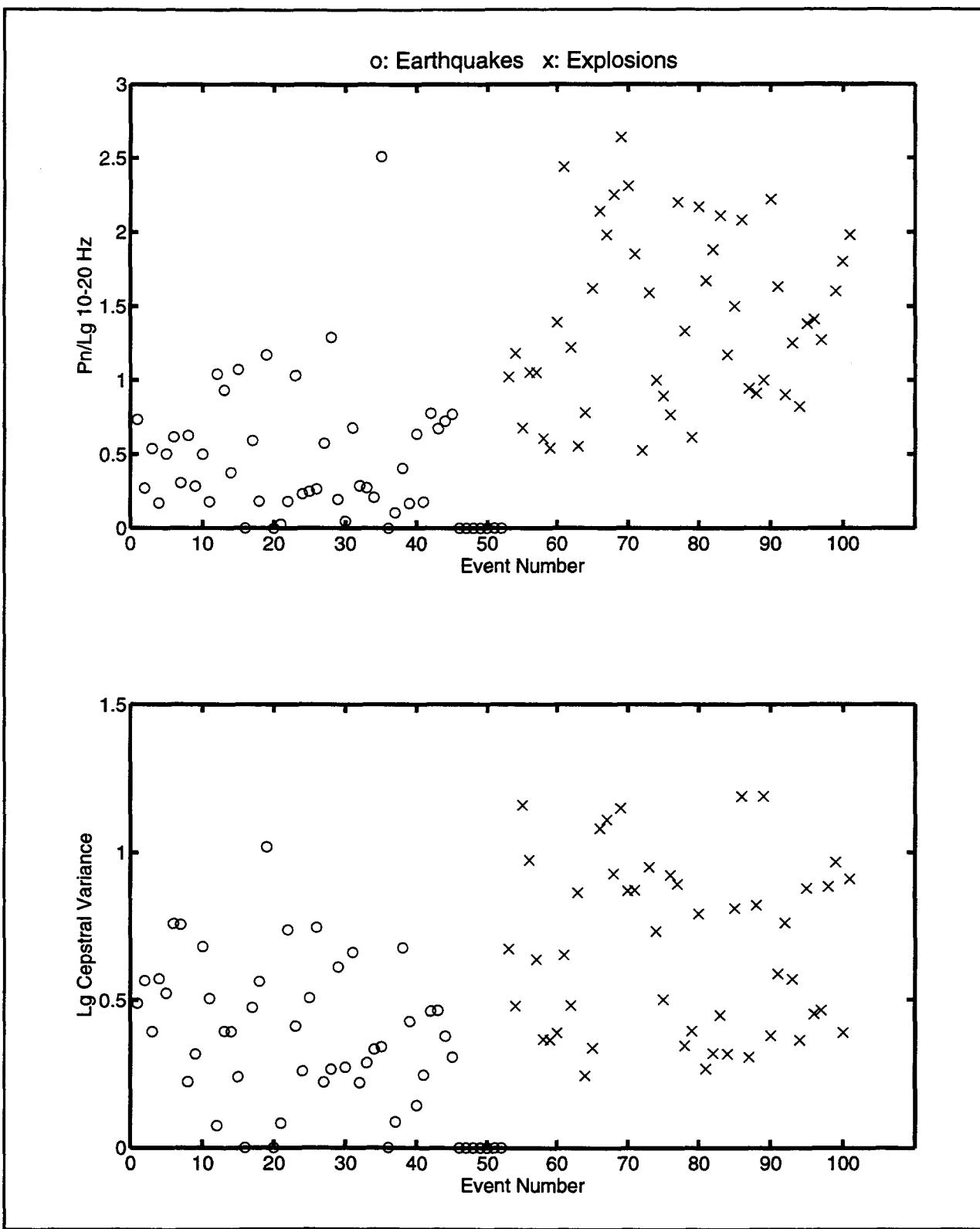


Figure 2. Examples of two spectral parameters measured at the NORESS array, tested for their ability to discriminate small earthquakes and explosions. The Pn/Lg spectral ratio measured from 10-20 Hz (top) provides good discrimination, though there is some overlap and one outlier. The Lg cepstral variance (bottom) is a poor discriminant.

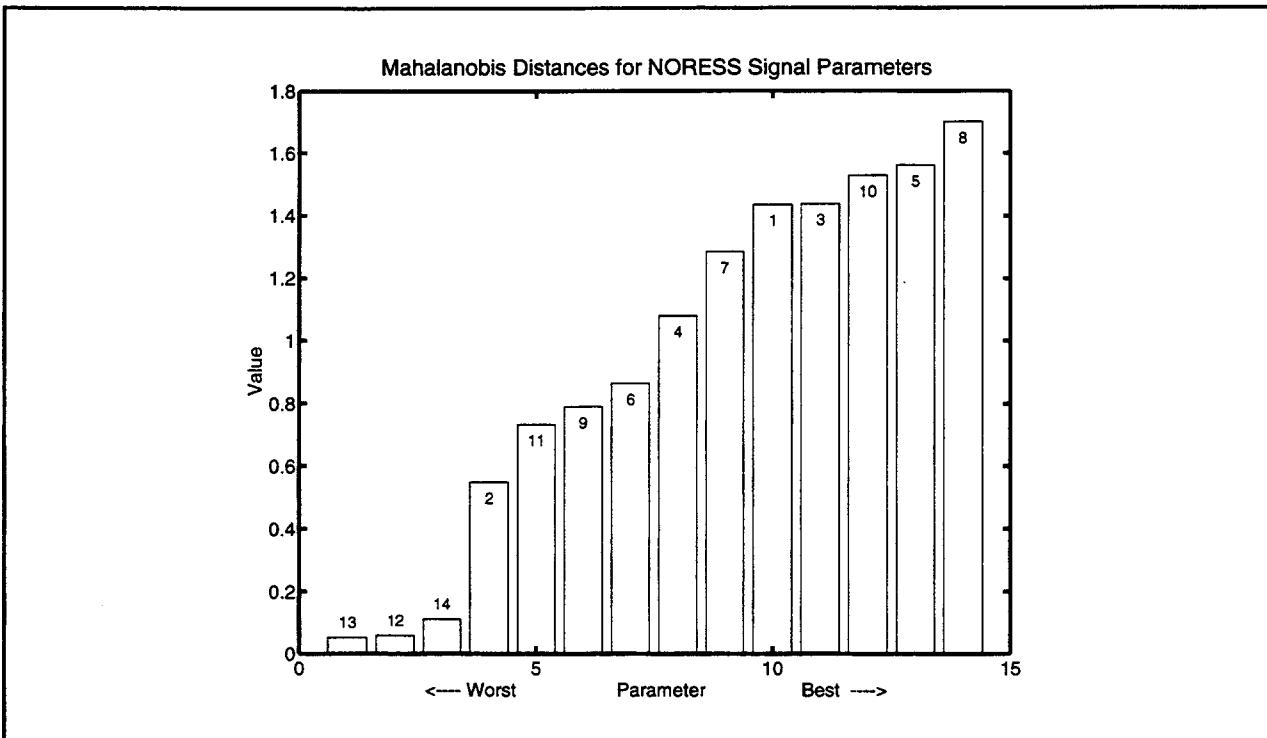


Figure 3. Mahalanobis Distances for the 14 signal parameters measured at the NORESS array. The parameters are: 1 - broadband Pn/Sn spectral ratio; 2 - Pn/Sn spectral ratio from 2-5 Hz; 3 - Pn/Sn spectral ratio from 5-10 Hz; 4 - Pn/Sn spectral ratio from 10-20 Hz; 5 - broadband Pn/Lg spectral ratio; 6 - Pn/Lg spectral ratio from 2-5 Hz; 7 - Pn/Lg spectral ratio from 5-10 Hz; 8 - Pn/Lg spectral ratio from 10-20 Hz; 9 - Pn cepstral variance; 10 - Sn cepstral variance; 11 - Lg cepstral variance; 12 - Pn third moment of frequency (TMF); 13 - Sn TMF; 14 - Lg TMF.

Real seismic signal parameter measurements are unlikely to ever replicate the ideal case shown in Figure 1D. There will always be scatter in the measurements. This scatter can either be real or due to measurement error. Real factors contributing to the scatter can be either source effects (source radiation patterns, source corner frequencies, etc.) or path effects (attenuation, scattering, or blockage). These factors can sometimes be accounted for using a larger azimuthal distribution of signal measurement or corrections to the data based on known effects (like Q). Measurement errors include both the effects of noise and the inaccuracy of the actual measurements, especially for spectral ratios.

2.3 Noise

Seismic measurements are (almost) always contaminated by noise. When we compute the Lg/P spectral ratio, we are actually computing the $(Lg+noise)/(P+noise)$ ratio. This is an important consideration for small magnitude events, as illustrated in Figure 4. The figure shows a simple model calculation of Lg/P vs. noise for an Lg/P of 2.0, typical for a small earthquake near NORESS. The noise, which is additive for both phases, varies from 1 to 30 (with respect to P). It is only when the

SNR reaches 5 that the measured spectral ratio is in error by less than 10%. Regional P-wave SNR's are generally lower than 10 in most frequency bands.

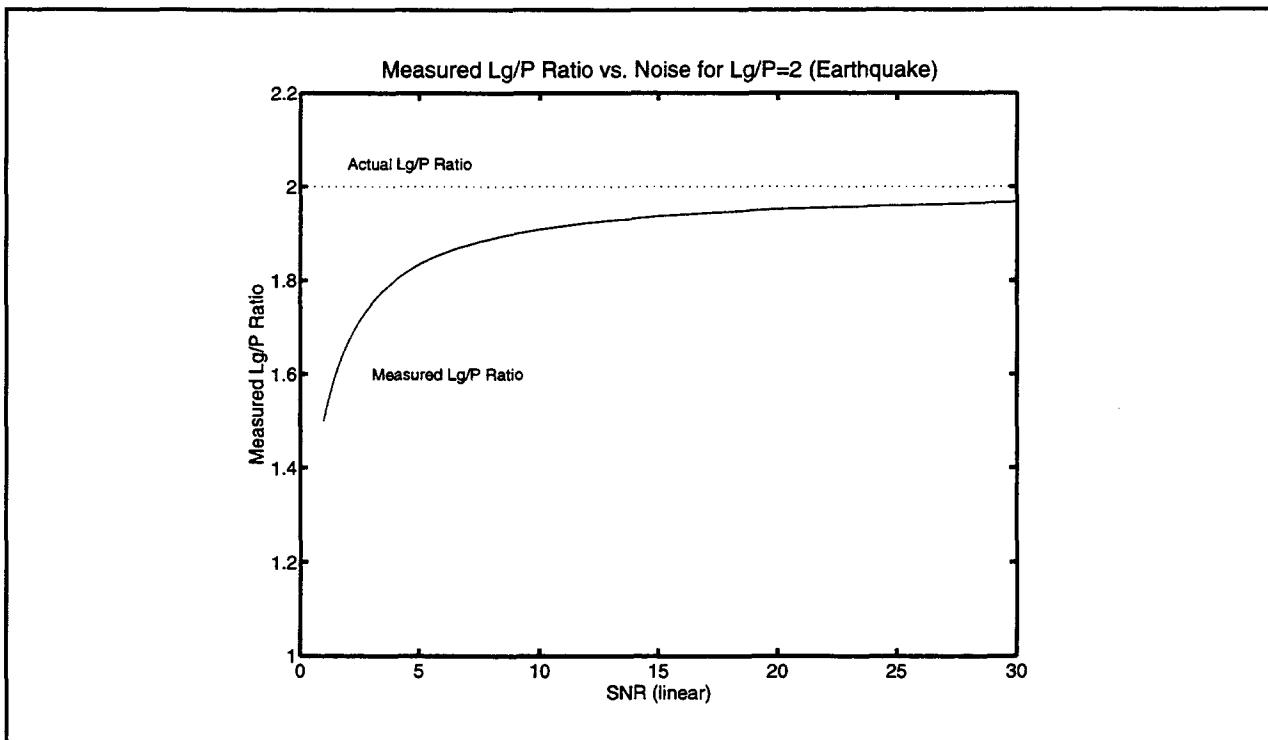


Figure 4. Predicted Lg/P spectral ratios vs. noise for a typical regional earthquake at NORESS where the actual Lg/P is 2. The noise, which is additive for both phases, varies from an SNR of 1 to 30 (with respect to P). When the SNR is low, the measurement is likely to be in error, adding to identification uncertainty.

2.4 Instability of Spectral Ratios and the Motivation for Cross Spectra

The use of spectral ratios in the parameterization approach is certainly appropriate, given the nature of source excitation for earthquakes and explosions. But regional seismic spectra rarely follow the model of a flat low-frequency spectrum with smooth high-frequency rolloff. This is especially true for quarry explosions, where long time-delay ripple firing can add harmonic distortion. Good signal processing practice dictates that measurements be made only at frequencies where there is sufficient SNR, which often means the use of cross spectral and system identification methods.

Even earthquakes and mining-induced events can exhibit enough spectral complexity to render common-band spectral ratios unrealistically too large or small. For example, Figure 5 shows Lg and Pn spectra for a mining-induced earthquake in the Lubin Copper Basin, recorded at GERESS. Because of spectral complexity, the spectral ratio shows peaks at narrow bands. Smoothing the spectra, a common practice in seismology, would help but would result in an inaccurate representation of the true ratios.

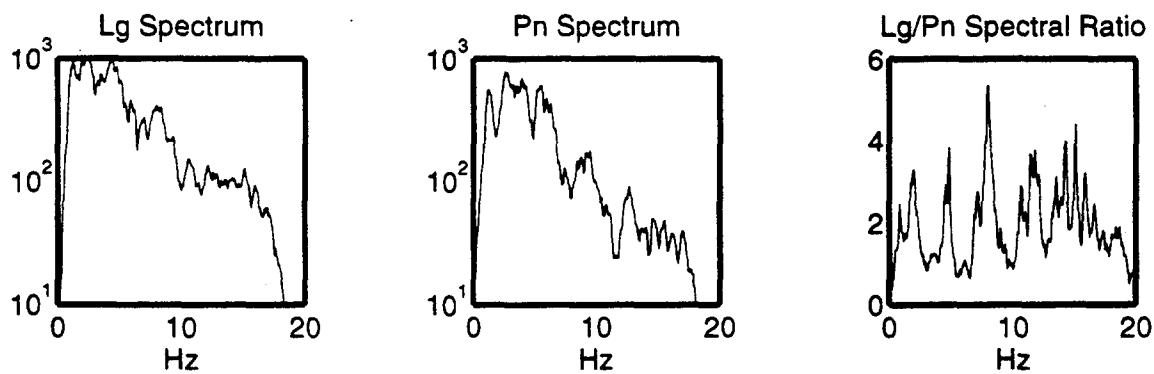


Figure 5. Lg and Pn spectra for a mining-induced earthquake in the Lubin Copper Basin, recorded at GERESS. Because of spectral complexity, the spectral ratio shows peaks at narrow bands. Smoothing the spectra, a common practice in seismology, would help but would result in an inaccurate representation of the true ratios.

Figure 6 shows another view of these same spectra, this time with the f^2 spectral decay removed. Note that the Lg and Pn spectra have peaks at different frequencies. Prudent signal processing dictates that measurements be made where there is signal energy. Use of cross band spectral ratios at energetic frequencies should reduce parameter variance and increase the certainty of source identification.

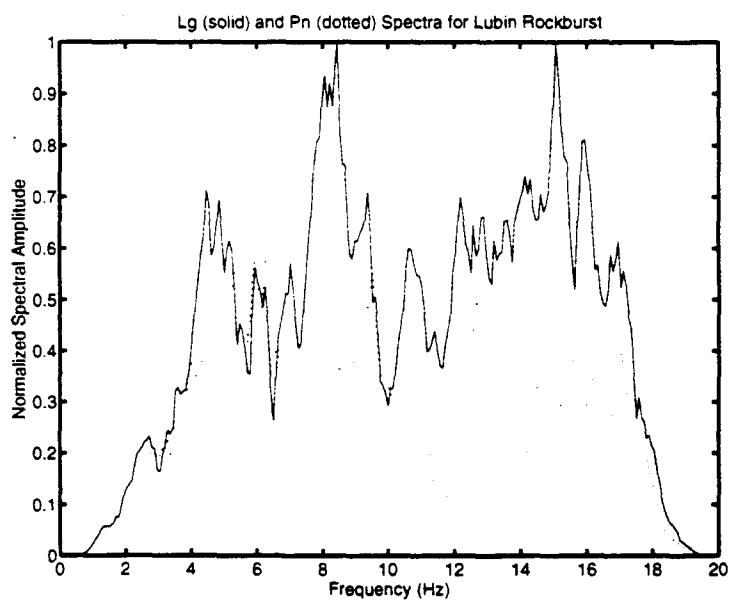


Figure 6. Lg and Pn spectra for a mining-induced earthquake in the Lubin Copper Basin (same as Figure 5). Both spectra have been corrected for f^2 spectral decay. The Lg and Pn spectral energy is concentrated in narrow bands which are not coincident, leading to peaks in the common-band spectral ratio.

3. RECOMMENDATIONS AND FUTURE PLANS

This project is just beginning, and the author solicits the assistance of any researchers in this program who have seismic waveform data for events with independently verified source type.

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